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Residue formulas for singular foliations defined by meromorphic functions on surfaces

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1 Baum-Bott residue of singular foliation on surfaces

In this article, let X be a two dimensional complex manifold (complex surface). A dimension one singular foliation \mathcal{E} on X is defined by a system $\{(U_\alpha, v_\alpha)\}$, where $\{U_\alpha\}$ is an open covering X and v_α is a holomorphic vector field on U_α for each α , such that $v_\beta = e_{\alpha\beta}v_\alpha$ on $U_\alpha \cap U_\beta$ for some non-vanishing holomorphic function $e_{\alpha\beta}$ on $U_\alpha \cap U_\beta$.

Let $S(v_\alpha)$ be a zero-set of v_α on U_α . The condition $v_\beta = e_{\alpha\beta}v_\alpha$, we have $S(v_\alpha) = S(v_\beta)$ on $U_\alpha \cap U_\beta$. Therefore we can define the singular set $S(\mathcal{E})$ of \mathcal{E} by $S(\mathcal{E}) = \cup_\alpha S(v_\alpha)$. We say \mathcal{E} is reduced if $S(\mathcal{E})$ consists of only isolated points. Since $\{e_{\alpha\beta}\}$ satisfies the cocycle condition, $e_{\alpha\beta} = e_{\alpha\gamma}e_{\gamma\beta}$ on $U_\alpha \cap U_\beta \cap U_\gamma$, it defines a line bundle E .

A singular foliation can also be defined in terms of holomorphic 1-forms. A codimension one singular foliation \mathcal{F} on X is defined by a system $\{(U_\alpha, \omega_\alpha)\}$, where ω_α is a holomorphic 1-form on U_α for each U_α such that $\omega_\beta = f_{\alpha\beta}\omega_\alpha$ on $U_\alpha \cap U_\beta$ for some non-vanishing holomorphic function $f_{\alpha\beta}$ on $U_\alpha \cap U_\beta$.

Similarly to the case of vector field, we can define the singular set $S(\mathcal{F})$ by $S(\mathcal{F}) = \cup_\alpha S(\omega_\alpha)$, where $S(\omega_\alpha)$ is the zero-set of ω_α on U_α . We say \mathcal{F} is reduced if $S(\mathcal{F})$ consists of only isolated points. A line bundle F is determined by the cocycle $\{f_{\alpha\beta}\}$.

These two definitions are equivalent as long as we consider reduced foliations. There is a natural one-to-one correspondence as following.

$$\mathcal{E} = \{(U_\alpha, v_\alpha)\} \xrightleftharpoons[\langle v_\alpha, \omega_\alpha \rangle = 0]{\text{annihilator}} \mathcal{F} = \{(U_\alpha, \omega_\alpha)\}$$

In this correspondence, $S(\mathcal{F}) = S(\mathcal{E})$, the integral curves of v_α are equal to the solution of $\omega_\alpha = 0$ (See [Sw]). Hence we consider only reduced foliations in what follows.

*This is a joint work with Tatsuo Suwa. I would like to thank him and Lê Dũng Tráng for suggesting the problem and for helpful conversations.

Let \mathcal{E} be a one dimensional reduced singular foliation. For each point $p \in S(\mathcal{E})$ and a homogeneous and symmetric polynomial ψ in degree two, we have the Baum-Bott residue $\text{Res}_\psi(\mathcal{E}, p) \in \mathbb{C}$ as following.

Suppose $(U_\alpha, (x, y))$ is a coordinate neighborhood with the origin p , and p is the isolated zero of the vector field $v = a(x, y)\frac{\partial}{\partial x} + b(x, y)\frac{\partial}{\partial y}$ on U , where v defines \mathcal{E} on U . Let A be the Jacobian $\frac{\partial(a, b)}{\partial(x, y)}$, $\sigma_1 = X_1 + X_2$, $\sigma_2 = X_1 X_2$, i.e. the elementary symmetric functions in two variables. We set

$$\sigma_1(A) = \text{trace} A, \quad \sigma_2(A) = \det A.$$

ψ can be written as $\psi = \tilde{\psi}(\sigma_1, \sigma_2)$ by some polynomial $\tilde{\psi}$. We set $\psi(A) = \tilde{\psi}(\sigma_1(A), \sigma_2(A))$. Then the Baum-Bott residue $\text{Res}_\psi(\mathcal{E}, p)$ is given by the integral

$$\text{Res}_\psi(\mathcal{E}, p) = \left(\frac{1}{2\pi\sqrt{-1}} \right)^2 \int_\Gamma \frac{\psi(A) dx \wedge dy}{ab},$$

where $\Gamma = \{(x, y) \in U \mid |a(x, y)| = |b(x, y)| = \varepsilon\}$ for a sufficiently small positive number ε and is oriented $\deg a \wedge \deg b > 0$. In particular when $\psi = \sigma_2$, the residue $\text{Res}_\psi(\mathcal{E}, p)$ is equal to $(a, b)_p$, the index of v at p . If v is global, we get Poincaré-Hopf formula. We denote by TX the holomorphic tangent bundle of X . The following theorem is known. (See [BB].)

Theorem 1.1 (Baum-Bott) *If X is compact, we have*

$$\sum_{p \in S(\mathcal{E})} \text{Res}_\psi(\mathcal{E}, p) = \psi(TX - E) \cap [X],$$

where, denoting by $c_1 = c_1(TX - E)$ and $c_2 = c_2(TX - E)$ the first and second Chern classes of the virtual bundle of $TX - E$, we set $\psi(TX - E) = \tilde{\psi}(c_1, c_2)$.

Let \mathcal{F} and F be the codimension one foliation corresponding to \mathcal{E} and the line bundle associated with \mathcal{F} respectively. We have following lemma and proposition. For line bundles L_1 and L_2 , we denote $c_1(L_1)c_1(L_2) \cap [X]$ by $L_1 \cdot L_2$.

Lemma 1.2 *$F = E \otimes K$, where K is a canonical bundle of X .*

Proposition 1.3 *If X is compact, we have*

$$\begin{aligned} \sum_{p \in S(\mathcal{F})} \text{Res}_{\sigma_1^2}(\mathcal{E}, p) &= F^2 \\ \sum_{p \in S(\mathcal{F})} \text{Res}_{\sigma_2}(\mathcal{E}, p) &= \chi(X) - K \cdot F + F^2, \end{aligned}$$

where $\chi(X)$ is Euler number of X .

2 Singular foliations defined by meromorphic functions

Let φ be a meromorphic function on X . Take a coordinate covering $\mathcal{U} = \{U_\alpha\}$ of X such that on each U_α , the differential $d\varphi$ of φ is written as $d\varphi = \varphi_\alpha \omega_\alpha$ where ω_α is a holomorphic 1-form with isolated zeros on U_α and φ_α is a meromorphic function on U_α . Then the system $\{(U_\alpha, \omega_\alpha)\}$ determines a singular foliation \mathcal{F} which is reduced and codimension one. The associated line bundle F is defined by the cocycle $\{f_{\alpha\beta}\}$, where $f_{\alpha\beta} = \frac{\varphi_\alpha}{\varphi_\beta}$. The leaves of \mathcal{F} are the level sets of φ .

Let $D^{(0)}$, $D^{(\infty)}$ be a zero and pole divisor of φ , respectively. $D^{(0)} = \sum_{j=1}^s n_j D_j^{(0)}$ and $D^{(\infty)} = \sum_{i=1}^r m_i D_i^{(\infty)}$ are irreducible decompositions. We denote by $|D|$ the support of D and by $[D]$ the line bundle determined by D .

Lemma 2.1 *If the critical points of φ in $X - |D^{(\infty)}|$ are all isolated, then we have $F = [-\sum_{i=1}^r (m_i + 1)D_i^{(\infty)}]$.*

Under the assumption of this lemma,

$$\begin{aligned} S(\mathcal{F}) \cap (X - |D^{(\infty)}|) &= \{\text{the critical point of } \varphi\} \\ S(\mathcal{F}) \cap |D^{(\infty)}| &\supset D^{(0)} \cap D^{(\infty)} \quad (\text{indeterminacies of } \varphi) \\ &\quad D_i^{(\infty)} \cap D_j^{(\infty)} \quad (\text{singularities of } D^{(\infty)}) . \end{aligned}$$

Hereafter we assume that the critical point of φ in $X - |D^{(\infty)}|$ are all isolated. We denote by \mathcal{E} the dimension one foliation corresponding to \mathcal{F} , which is an annihilator of \mathcal{F} .

Lemma 2.2 *For the singular point p of \mathcal{E} in $X - |D^{(\infty)}|$, we have*

$$\text{Res}_{\sigma_1^2}(\mathcal{E}, p) = 0, \quad \text{Res}_{\sigma_2}(\mathcal{E}, p) = \mu_p(\varphi),$$

where $\mu_p(\varphi)$ is the Milnor number of φ at p .

In what follows, for divisors D_1 and D_2 , we denote by $(D_1, D_2)_p$ the intersection number at p and by $D_1 \cdot D_2$ the total intersection number.

Lemma 2.3 *For the singular point p of \mathcal{E} in $|D^{(\infty)}|$, we have*

$$\text{Res}_{\sigma_1^2}(\mathcal{E}, p) = \sum_{i=1}^r \frac{(m_i + 1)^2}{m_i} (D^{(0)}, D^{(\infty)})_p - \sum_{1 \leq i < j \leq r} \frac{(m_i - m_j)^2}{m_i m_j} (D_i^{(\infty)}, D_j^{(\infty)})_p.$$

Thus if p is not an intersection point of $D^{(0)}$ and $D_i^{(\infty)}$ or of $D_i^{(\infty)}$ and $D_j^{(\infty)}$ which is $m_i \neq m_j$ then $\text{Res}_{\sigma_1^2}(\mathcal{E}, p) = 0$.

Set $D = \sum_{i=1}^r (m_i + 1)D^{(\infty)}$ which may be called the pole divisor of $d\varphi$. From the above (2.2) and (2.3), we get following.

Proposition 2.4 *Let φ be a meromorphic function on a compact complex surface X . If the critical points of φ in $X - |D^{(\infty)}|$ are all isolated, we have*

$$D^2 = \sum_p \left(\sum_{i=1}^r \frac{(m_i + 1)^2}{m_i} (D^{(0)}, D^{(\infty)})_p - \sum_{1 \leq i \leq j \leq r} \frac{(m_i - m_j)^2}{m_i m_j} (D_i^{(\infty)}, D_j^{(\infty)})_p \right) \\ \sum_{p \in S(\mathcal{E}) \cap (X - |D|)} \mu_p(\varphi) + \sum_{p \in S(\mathcal{E}) \cap |D|} \text{Res}_{\sigma_2}(\mathcal{E}, p) = \chi(X) + D^2 + K \cdot D$$

Remark 2.5 *We call the quantity $\frac{1}{2}(D^2 + K \cdot D) + 1$ the “virtual genus” of a divisor of D (See [K]). Then we may define the “virtual euler number” of a divisor D by $\chi'(D) = -(D^2 + K \cdot D)$. (c.f. $\chi(X) = 2 - 2g(X)$) With this the second equation of (2.4) is written as*

$$\sum_{p \in S(\mathcal{E}) \cap (X - |D|)} \mu_p(\varphi) + \sum_{p \in S(\mathcal{E}) \cap |D|} \text{Res}_{\sigma_2}(\mathcal{E}, p) = \chi(X) - \chi'(D)$$

3 Foliations arising from polynomials

Let $f(x, y)$ be a polynomial of degree d with complex coefficients. Consider the rational function φ_0 on $\mathbf{P}^2 = \{[\zeta_0, \zeta_1, \zeta_2]\}$ given by

$$\varphi_0(\zeta_0, \zeta_1, \zeta_2) = \frac{\tilde{f}(\zeta_0, \zeta_1, \zeta_2)}{\zeta_0^d},$$

where $\tilde{f}(\zeta_0, \zeta_1, \zeta_2)$ is a homogenized polynomial of f . Suppose that the critical points of f are all isolated. Thus $\frac{\partial f}{\partial x}$ and $\frac{\partial f}{\partial y}$ are relatively prime and f is reduced.

We denote by \mathcal{F} the singular foliation on \mathbf{P}^2 defined by φ_0 . The pole divisor of φ_0 is dL_∞ , where L_∞ is the infinite line $\{\zeta_0 = 0\}$. Thus the line bundle F corresponding to \mathcal{F} is given by $F = [-(d+1)L_\infty]$.

Let $U_i = \{\zeta_i \neq 0\} \subset \mathbf{P}^2$ ($i = 1, 2, 3$). On the finite part $U_0 = \mathbf{C}^2 \subset \mathbf{P}^2$, \mathcal{F} is defined by df . By assumption the critical points of f are all isolated, we have $S(\mathcal{F}) \cap U_0 = C(f)$, the set of critical points of f on U_0 . Now we consider in the infinite part of \mathbf{P}^2 . We work on U_2 however it is similar on U_1 . We can assume that $f_d(x, y)$ is not divisible by y , where $f_d(x, y)$ is a homogeneous piece of degree d of f . Then $S(\mathcal{F}) \cap L_\infty \subset U_2$. We take $(u, v) = \left(\frac{\zeta_0}{\zeta_2}, \frac{\zeta_1}{\zeta_2}\right)$ as a coordinate system on U_2 . The function φ_0 is written as $\varphi_0(u, v) = \frac{\hat{f}(u, v)}{u^d}$ on U_2 , where $\hat{f}(u, v) = \tilde{f}(u, v, 1)$. On U_2 , \mathcal{F} is defined by

$$\omega = \left(u \frac{\partial \hat{f}}{\partial u} - d \cdot \hat{f} \right) du + u \frac{\partial \hat{f}}{\partial v} dv.$$

Now since $S(\mathcal{F}) \cap L_\infty = \{u = f_d(v, 1) = 0\}$, the set of intersection points $D^{(0)}$ and $D^{(\infty)}$, and $D^{(\infty)}$, by (2.3), we have

$$\text{Res}_{\sigma_1^2}(\mathcal{E}, p) = \frac{(d+1)^2}{d} m_p(f), \quad p \in S(\omega) \cap L_\infty,$$

where $m_p(f) = (D^{(0)}, L_\infty)_p$. Since $\sum m_p(f) = d$, the formula $\sum \text{Res}_{\sigma_1^2} = F^2$ is a tautology.

The foliation \mathcal{E} corresponding to \mathcal{F} is defined by the vector field $u \frac{\partial \hat{f}}{\partial v} \frac{\partial}{\partial u} - \left(u \frac{\partial \hat{f}}{\partial u} - d \cdot \hat{f}\right) \frac{\partial}{\partial v}$ on U_2 . For the singular point p of \mathcal{E} in $L_\infty \cap U_2$, we can calculate $\text{Res}_{\sigma_2}(\mathcal{E}, p)$ as following.

$$\begin{aligned} \text{Res}_{\sigma_2}(\mathcal{E}, p) &= \left(u \frac{\partial \hat{f}}{\partial v}, u \frac{\partial \hat{f}}{\partial u} - d \cdot \hat{f}\right)_p \\ &= (u, \hat{f})_p + \left(u \frac{\partial \hat{f}}{\partial v}, u \frac{\partial \hat{f}}{\partial u} - d \cdot \hat{f}\right)_p \\ &= m_p(f) + I_2, \end{aligned}$$

where $I_2 = \left(u \frac{\partial \hat{f}}{\partial v}, u \frac{\partial \hat{f}}{\partial u} - d \cdot \hat{f}\right)_p$. In order to calculate I_2 , let $\frac{\partial \hat{f}}{\partial v} = h_1^{m_1} h_2^{m_2} \cdots h_l^{m_l}$ be a irreducible decomposition at p and $\pi(t) = (u(t), v(t))$ a uniformalization of $h_i = 0$. Now if we write

$$\hat{f}(\pi(t)) = \sum_{n \geq q_i} a_n t^n, \quad \frac{\partial \hat{f}}{\partial u}(\pi(t)) = \sum_{n \geq r} b_n t^n, \quad u(t) = \sum_{n \geq s} c_n t^n$$

with $a_{q_i}, b_r, c_s \neq 0$. From $\frac{d\hat{f}}{dt}(\pi(t)) = \frac{\partial \hat{f}}{\partial u}(\pi(t)) \frac{du}{dt}$,

$$q_i = r + s, \quad n a_n = \sum_{k=s}^{n-r} k c_k b_{n-k} \quad (n \geq q_i).$$

Thus we may write

$$\left(u \frac{\partial \hat{f}}{\partial u} - d \cdot \hat{f}\right)(\pi(t)) = \sum_{n \geq q_i} \left(\sum_{k=s}^{n-r} c_k b_{n-k} - d a_n\right) t^n.$$

We denote the order of this power series by $q_i + \delta_i$. Since $q_i = (h_i, u \frac{\partial \hat{f}}{\partial u})_p$, we have

$$\begin{aligned} I_2 &= \sum_{i=1}^l m_i q_i + \sum_{i=1}^l m_i \delta_i = \left(\frac{\partial \hat{f}}{\partial v}, u \frac{\partial \hat{f}}{\partial u}\right)_p + \delta_p \\ &= \left(\frac{\partial \hat{f}}{\partial v}, u\right)_p + \left(\frac{\partial \hat{f}}{\partial v}, \frac{\partial \hat{f}}{\partial u}\right)_p + \delta_p = \mu_p(\hat{f}) + m_p(f) - 1 + \delta_p, \end{aligned}$$

where $\delta_p = \sum_{i=1}^l m_i \delta_i$. The number δ_p is referred to as the “value of a jump in Milnor number at ∞ ” by D.T.Lê. In general $\delta_p = 0$. Thus we have

$$\text{Res}_{\sigma_2}(\mathcal{E}, p) = \mu_p(\hat{f}) + 2m_p(f) - 1 + \delta_p$$

Since $\chi(\mathbf{P}^2) = 3$, $K_{\mathbf{P}^2} = -3L_\infty$, $D = (d+1)L_\infty$, $L_\infty^2 = 1$, $\sum m_p(f) = d$, we have the following formula.

Theorem 3.1

$$\sum_{p \in C(f)} \mu_p(f) + \sum_{i=1}^k (\mu_{p_i}(\hat{f}) + \delta_{p_i} - 1) = d^2 - 3d + 1,$$

where, letting $f_d(x, y) = \prod_{i=1}^k (b_i x - a_i y)^{d_i}$, $p_i = [0, a_i, b_i]$, $m_{p_i}(f) = d_i$.

This formula is also obtained by D.T.Lê in the case f has no critical points. (not published.)

Next we consider the compactification $\pi : X \rightarrow \mathbf{P}^2$ of f as constructed by D.T.Lê and C.Webber (See [LW]). The set $A(f)$ of atypical values of f is expressed as $A(f) = D(f) \cup I(f)$, where $D(f)$ is the set of critical values of f and $I(f)$ is determined by the behavior of f at infinity. Then the compactification $\pi : X \rightarrow \mathbf{P}^2$ is obtained from \mathbf{P}^2 by a finite sequence of blowing up “points at infinity” and have following properties.

- (1) X is a compact complex surface and π is a proper holomorphic map inducing a biholomorphic map of $X - \pi^{-1}(L_\infty)$ onto $\mathbf{P}^2 - L_\infty = \mathbf{C}^2$.
- (2) $\pi^{-1}(L_\infty)$ is a union of projective lines with normal crossings.
- (3) The meromorphic function $\varphi = \varphi_0 \circ \pi$ does not have indeterminacy points, where $\varphi_0 = \frac{f}{\zeta_0^d}$. Thus we may think of $\varphi : X \rightarrow \mathbf{P}^1$ as a holomorphic map.
- (4) For $\lambda \in \mathbf{C} - I(f)$, π gives an imbedded resolution of the singularities of the curve $C_\lambda : \tilde{f} - \lambda \zeta_0^d = 0$ on L_∞ .

Moreover, if we denote by \mathcal{A} and \mathcal{A}_∞ , respectively, the intersection graphes of the divisor $\pi^{-1}(L_\infty)$ and the pole divisor of φ ,

- (5) \mathcal{A} is a connected tree and \mathcal{A}_∞ is a connected sub-tree of \mathcal{A} .
- (6) Each connected component of $\mathcal{A} - \mathcal{A}_\infty$ is a bamboo which contains a unique dicritical component (a component of $\pi^{-1}(L_\infty)$ on which φ is not constant).

Let \mathcal{E} be the foliation on X which is determined by φ and $D^{(\infty)} = \sum_{i=1}^r m_i D_i^{(\infty)}$ be the pole divisor of φ . We assume all the critical points of φ are isolated. Then there are two types of singularities of \mathcal{E} .

- (a) critical points of φ on $X - |D^{(\infty)}|$,
- (b) intersection points in $D^{(\infty)}$.

For the type (a) singularity p , $\text{Res}_{\sigma_1}(\mathcal{E}, p) = 0$ and $\text{Res}_{\sigma_2}(\mathcal{E}, p) = \mu_p(\varphi)$ as before. For the type (b) singularity p , $\text{Res}_{\sigma_1^2}(\mathcal{E}, p) = -\frac{(m_i - m_j)^2}{m_i m_j}$ if p is an intersection point of $D_i^{(\infty)}$ and $D_j^{(\infty)}$. On the neighborhood of the type (b) singularity p , we can write $\mathcal{E} = x \frac{\partial}{\partial x} - y \frac{\partial}{\partial y}$. Then $\text{Res}_{\sigma_2}(\mathcal{E}, p) = (x, y)_p = 1$. Again we set $D = \sum_{i=1}^r (m_i + 1) D_i^{(\infty)}$, then $\sum \text{Res}_{\sigma_1^2}(\mathcal{E}, p) = F^2$ becomes

$$D^2 = - \sum_{1 \leq i < j \leq r} \frac{(m_i - m_j)^2}{m_i m_j} \delta_{ij}, \quad \delta_{ij} = \begin{cases} 0 & \text{when } D_i^{(\infty)} \text{ meets } D_j^{(\infty)} \\ 1 & \text{otherwise} \end{cases}.$$

We recall $D(f) \subset A(f)$, then $\sum \text{Res}_{\sigma_2}(\mathcal{E}, p) = \chi(X) + K \cdot D + D^2$ becomes

$$\sum_{\lambda \in A(f)} \mu(X_\lambda) + l = \chi(X) - \chi'(D),$$

where $\mu(X_\lambda)$ is a total Milnor number of $X_\lambda = \{\varphi = \lambda\}$ and l is the number of intersection points of $D^{(\infty)}$. The last equation may be thought of as a “Milnor number formula” in the presence of multiple fibers. In fact, we assume that $D^{(\infty)}$ is reduced. We obtain the Milnor number formula in the two dimensional case. (See also [TT])

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